Modeling of dark current in mid-IR QWIPs

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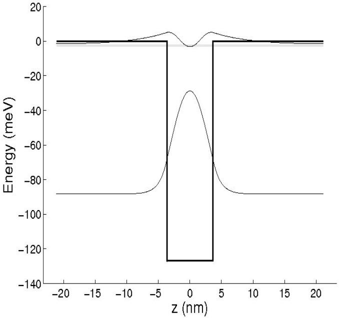
Motivations

- device dark current is the limiting factor for cold-background detection
- I(V) features below 20 K still to be explained

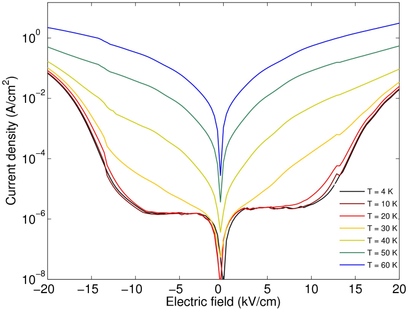
Outline

- Device/Experiment
- Modeling
- Results

Experiment

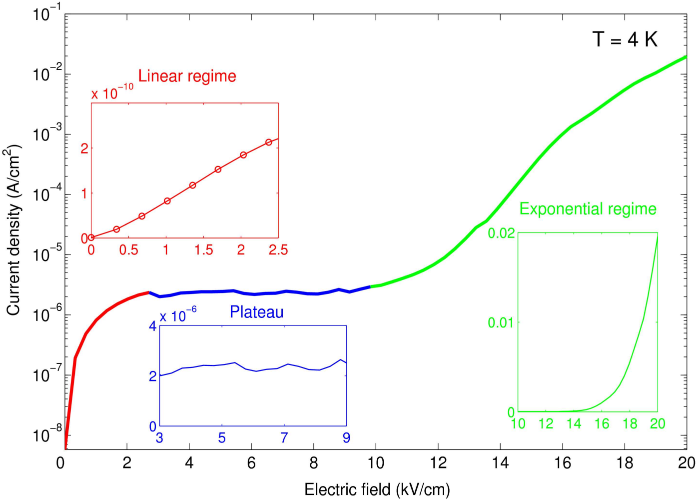


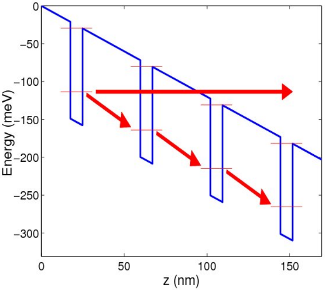
- GaAs/$Al_{0.15}Ga_{0.85}As$ QWIP
- 7.3 nm well - 45 nm barrier
- 40 periods
- $\Delta E = 85.5$ meV/20.6 THz/14.5 μm

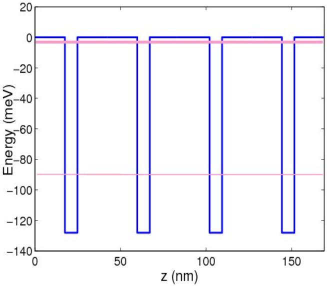


- Thermionic regime:
  $T \geq 40$ K
- Tunneling regime:
  $T \leq 20$ K

Tunneling current regimes

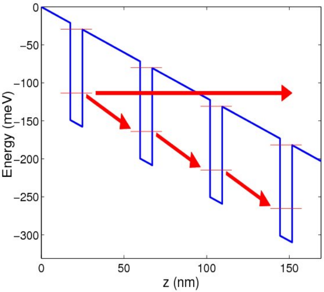


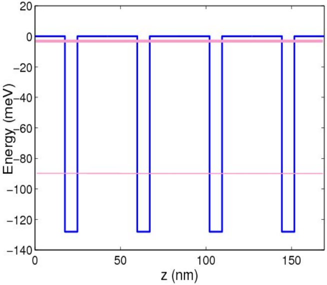




At low temperature current is due to electrons in the ground state.

Low temperature current contributions





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Wannier-Stark picture

- Seq. tunneling between ground states (low field)
- Direct tunneling into continuum (high field)

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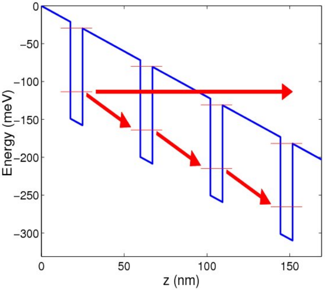

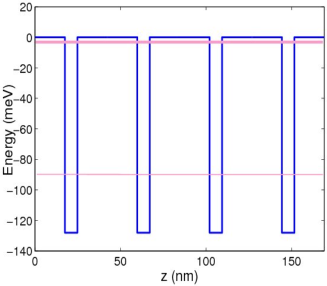

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Miniband picture

- Miniband transport (low field)
- Interminiband Zener transitions (high field)

Basic idea

- Select appropriate description for each current component

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- Select appropriate description for each current component
- Field assisted emission dominates at high fields $\rightarrow$ Wannier-Stark picture
- Tunneling between ground states dominates at low fields $\rightarrow$ miniband picture
- Sum everything

$$j = \sum_{\nu} j_{\nu} + j_{\nu \to c}$$

Low bias: semiclassical miniband model

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Sinusoidal miniband approximation

$$E(\mathbf{k}) = E_0 + \frac{\epsilon}{2}(1 - \cos(k_z L)) + \frac{\hbar^2 k_\parallel^2}{2m}$$

$$\mathbf{v}(\mathbf{k}) = \frac{1}{\hbar}\nabla E$$

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Distribution function $f(\mathbf{k})$ and Boltzmann eq.

$$\frac{\partial f}{\partial t} = \frac{q}{\hbar}\mathbf{F} \cdot \nabla_{\mathbf{k}} f + S_\tau[f]$$

$$f(\mathbf{k};\mathbf{F}) = \left[1 + \exp\left(\frac{E(\mathbf{k} + \Delta\mathbf{k}(\mathbf{F},\tau)) - E_F}{k_B T}\right)\right]^{-1}$$

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Current densty

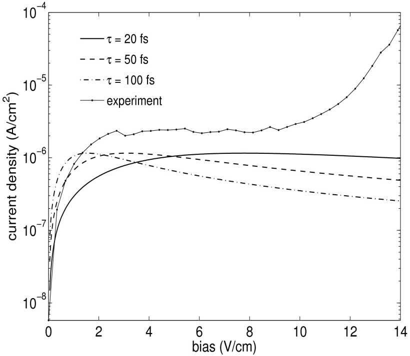
$$\mathbf{j} = q N_{3D} \frac{\int \mathbf{v}(\mathbf{k}) f(\mathbf{k}; \mathbf{F}) \mathrm{d}\mathbf{k}}{\int f(\mathbf{k}) \mathrm{d}\mathbf{k}}$$

Low bias: results

Very low coupling allows analitycal solution

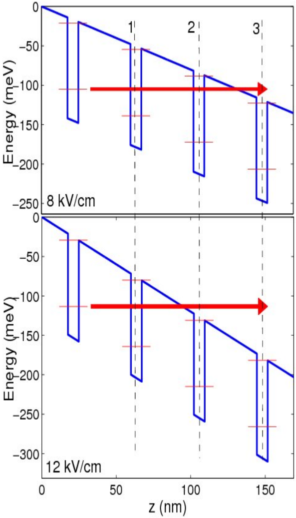
$$j_z(F) = N_{3D} \frac{F\tau}{\left(\frac{\hbar}{eL_z}\right)^2 + (F\tau)^2} \frac{\epsilon^2}{8E_F}$$

$$j_{sat} = \frac{eN_{3D}L_z\epsilon^2}{16\hbar E_F}$$



- Good fit up to 10kV/cm
- Plateau current independent of τ

High bias: transmission model



- Switch to Wannier-Stark picture

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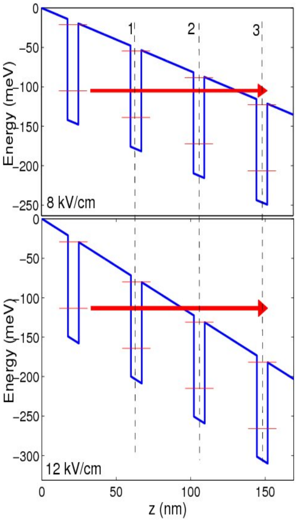

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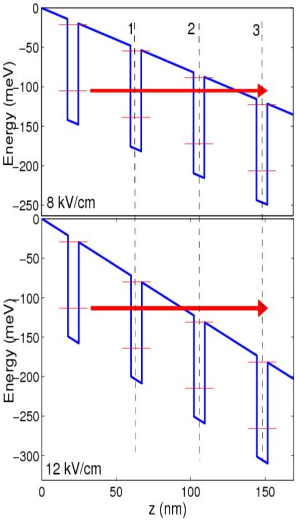
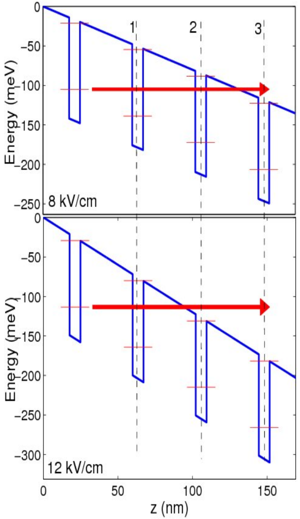
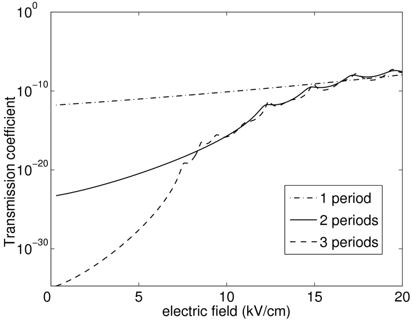


- Switch to Wannier-Stark picture
- Transmission through trapezoidal barriers
- Ground-continuum tunneling current

$$j_{0\rightarrow c} = eN_{2D}\frac{E}{h}\mathcal{T}(F)\ .$$

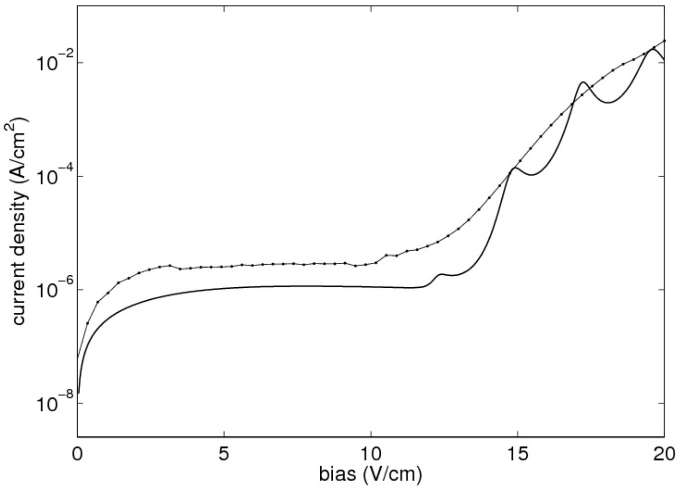
Transmission coefficient





- $\mathcal{T}(F)$ by modified transfer matrix
- Number of periods depends on field
- Important at low fields

Low temperature simulation: $\tau = 20$ fs, 2 periods



High temperature

Same model with thermal activation allows to simulate high temperature transport

$$j_{\nu\to c} = eN_{2D}\frac{k_B T}{E_F}\exp\left(-\frac{E_\nu - E_F - \eta eFL_w}{k_B T}\right)\frac{E_\nu}{h}\mathcal{T}_\nu(F).$$

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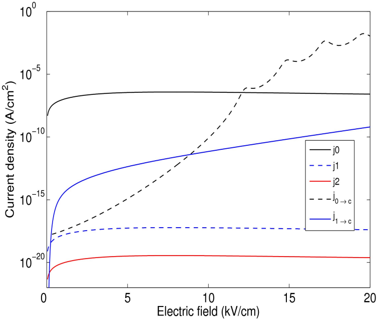
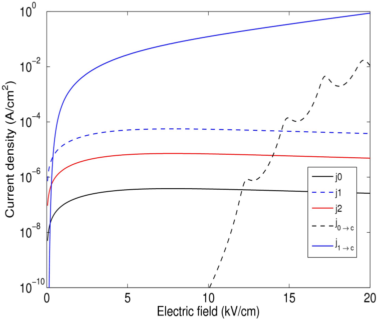


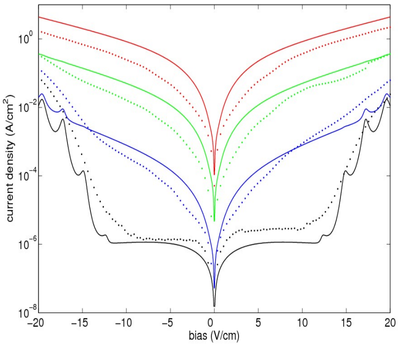
T = 20 K



T = 50 K

Full simulation

- Error within fluctuations due Al fraction and thickness uncertainty
- Unwanted resonances at high field due to lack of dissipation in the transmission model
- No free parameters in tunneling regime



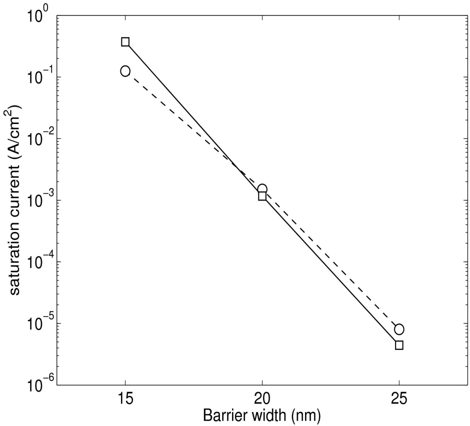
Plateau current check

Additional devices

- Al fraction: 26%
- well width: 5 nm
- barrier width: 15, 20, 25 nm

No free parameters

$$j_{sat} = \frac{eN_{3D}L_z\epsilon^2}{16\hbar E_F}$$



Summary

- Model for dark-current in QWIPs
- Agreement over large bias and temperature range
- Low temperature predictions without free parameters

Open issues and perspectives

- Doping dependence
- Link with microscopic models (See E. Luhillier at 3:50 pm)

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Thank you for your attention!